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LASER NET: A SYSTEM FOR MONITORING WINGTIP VORTICES ON RUNWAYS

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16. ABSTRACT

A laser schlieren method is proposed which potentially provides a means for monitoring the strength of vortex wakes on and near runways. The method could provide a gross, continuous assessment of the intensity of disturbances over airport runways and aircraft carriers. Preliminary measurements behind a wingtip mounted on the wall of a small subsonic wind tunnel indicate that wingtip vortices are readily detectable with this simple system.

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DEFINITION OF SYMBOLS

Symbol	Definition
c	speed of light in a vacuum
D	diameter of laser beam
E	signal voltage from total beam cross section
$e(t)$	fluctuating signal voltage
e_T	total signal formed by adding the signal from two or more beams
$\overline{e_{T_{RMS}}}$	root-mean-square of total signal with averaging time of T_1
$e'_{T_{RMS}}$	root-mean-square of total signal with averaging time of T_2 ($T_1 \gg T_2$)
h	height of laser beam above runway
ℓ	one-half the distance from laser to detector
m	number of laser beams in laser net
$\underline{N}$	unit vector normal to the laser beam
n	refractive index of air ($n = c/v$)
$r(y)$	distance from differential element of the beam to the knife-edge
s	laser schlieren sensitivity
t	time
v	speed of light in air
x,y,z	axes of coordinate system
α	Gladstone-Dale constant
β	angular deflection of laser beam
β_x	angular deflection of laser beam in horizontal plane

Symbol	Definition
$\Delta e_{T_{RMS}}$	"sudden" change in RMS value of total signal
$\underline{\Delta}$	beam deflection vector
Δ_x	the x-component of the beam deflection vector
ρ	instantaneous density of air

Subscript

RMS	root-mean-square

Superscript

$\overline{(\ )}$	time average

TECHNICAL MEMORANDUM X-64525

LASER NET: A SYSTEM FOR MONITORING WINGTIP VORTICES ON RUNWAYS

SUMMARY

This report proposes a method for monitoring the wingtip vortices which are created over the runway by a landing or ascending airplane. These vortices present a hazard to the next airplane which lands or takes off, particularly if the first airplane is large and the second one is small. The proposed system is referred to as a "laser net" because it is composed of a network of laser beams passing over the runway. The schlieren deflections of each of the beams is monitored by a photodetector and the resulting fluctuating signals are electronically added. The composite signal is amplified and its root-mean-square (RMS) value is computed. The magnitude of the RMS value of the composite signal is used to indicate whether or not unsafe conditions exist on the runway. Preliminary measurements of trailing vortices in a small subsonic wind tunnel indicated that wingtip vortices can be readily detected with the laser schlieren system.

The "laser net" requires the presence of towers (or poles) along the runway; however, if the poles are objectionable, they could be retracted underground during take-offs and landings.

I. INTRODUCTION

Unsafe conditions for take-off or landing can exist on airport runways for several minutes after an airplane has taken off or landed. This is a result of the strong wingtip vortex wakes left over the runway by the airplane. These vortices decay and move off the runway with time. However, uncontrollable variables, such as cross-wind speed, can influence the duration of the wingtip vortex hazard. Therefore, for more efficient and safer utilization of a runway, a monitoring system is needed to determine when conditions are safe for take-off or landing.

This report proposes a method which will potentially provide the means for monitoring the strength of vortex wakes left by airplanes on and near airport runways. The system is referred to herein as "laser net."

Laser net consists of a net of laser beams passing over the runway. The schlieren signals of each of these beams is monitored by a photodetector. The signals are added, amplified, and filtered. A vortex wake passing through one or more of the beams in the net can be detected by continuously monitoring the difference between two root-mean-square values of the composite signal, one averaged over a much

longer period of time than the other. The method is described in detail in the following discussion.

This technique is a spin-off from the laser-schlieren crossed-beam program initiated at Marshall Space Flight Center. In this program laser schlieren signals from turbulent flows with mean flow speeds as low as 13 meters per second have been retrieved without difficulty. Because the sensitivity of the laser schlieren system considered herein is approximately 100 times greater than that used in the laboratory, it is probable that schlieren fluctuations produced by a vortex wake passing through a laser net can be useful in a vortex monitoring system for airport runways.

II. THE TECHNIQUE

Figure 1 shows a laser and photodetector on opposite sides of a runway. The laser beam is directed over the runway at a constant height, h, perpendicular to the path of aircraft, and into the photodetector. The path of the beam from the laser to the detector is a straight line only when the air is undisturbed (i.e., there are no density gradients along the beam path). This is because the speed of light, v, depends on the properties of the medium through which it is traveling. For air the relationship is

$$n - 1 = \alpha\rho , \tag{1}$$

where n is the refractive index, ρ is the density of the air, and α is a constant. The refractive index is defined as the ratio of the speed of light in a vacuum, c, to the speed in some medium, v.

$$n = c/v. \tag{2}$$

If during its transit from laser to detector the beam encounters disturbances characterized by density gradients, the laser beam will be deflected from its undisturbed path (see figure 2). The magnitude of the deflection is related to the magnitude of the density gradients encountered. The local incremental angular deflection in a plane which includes the beam and the density gradient vector is given by [1]

$$d\beta = \frac{1}{n} \underline{N} \cdot \nabla n \, dy \tag{3}$$

where $\underline{N}$ is a unit vector normal to the beam and in the plane, described above, in which $d\beta$ is measured. The component of the incremental angular deflection of the beam in the x-y plane is given by [2]

$$d\beta_x = \frac{1}{n}\frac{\partial n}{\partial x}\, dy, \tag{4}$$

where the coordinate x is perpendicular and y is parallel to the beam path (see figure 1). To determine the total angular deflection of the beam in the horizontal plane, β_x, equation (4) must be integrated along the entire path of the beam.

$$\beta_x = \int_{-\ell}^{\ell} \frac{1}{n}\frac{\partial n}{\partial x}\, dy. \tag{5}$$

It is desirable to express β_x in terms of air density instead of refractive index. Thus, from equation (1),

$$\frac{\partial n}{\partial x} = \alpha \frac{\partial \rho}{\partial x} . \tag{6}$$

Using the fact that n for air is very near unity ($n \doteq 1.000292$), equation (5) can be simplified:

$$\beta_x \doteq \int_{-\ell}^{\ell} \frac{\partial n}{\partial x}\, dy. \tag{7}$$

Substitution of equation (6) into equation (7) yields

$$\beta_x \doteq \alpha \int_{-\ell}^{\ell} \frac{\partial \rho}{\partial x}\, dy. \tag{8}$$

Equation (8) shows that the angular deflection of the laser beam, in the horizontal plane, is directly related to the integral along the entire beam length of a component of the density gradient which is produced by an "invisible" disturbance. Further, the magnitude of the deflection increases with the magnitude of the disturbance.

The next step is to establish the means by which a go/no-go decision can be made from a visual display of the laser beam deflections. Shown in Figure 3 is a schematic of the method by which laser beam deflections can be monitored. The photodetector is composed of (1) a knife-edge which is positioned such that approximately 50 percent of the beam is blocked when the beam is in its undisturbed position, (2) a lens for focusing on the photodiode that part of the beam passing the knife-edge, and (3) a photodiode for monitoring the radiative power of that portion of the laser beam reaching it.

Figure 4, which illustrates the function of the knife-edge, is a view along the laser beam from the laser toward the detector and shows the knife-edge, the photodiode eye, and the laser beam cross section in both its undisturbed and typically disturbed positions. It is assumed that the deflections of the laser beam, as seen by the knife-edge, are small compared to the diameter of the beam, D. As a disturbance passes through the beam, the beam is deflected. Due to the presence of the knife-edge, the deflection will result in a change in the radiative power reaching the photodiode eye. The change, or fluctuation, may be either positive or negative depending upon the direction of deflection.

Let Δ_x be the x-component of the beam deflection at the knife-edge. Then,

$$e(t) = [4E/\pi D] \, \Delta_x(t), \tag{9}$$

where e(t) is the fluctuating signal voltage, D is the diameter of the beam, and E is the signal voltage from total beam cross section. Now, the differential displacement of the beam at the knife-edge due to a differential angular deflection of the beam at a distance r from the knife-edge is

$$d\Delta_x = r \cdot d\beta_x. \tag{10}$$

Integrating equation (10) along the beam using equations (4) and (6) we obtain:

$$\Delta_x = \alpha \int_{-\ell}^{\ell} r \frac{\partial\rho}{\partial x}\, dy. \tag{11}$$

Substituting equation (11) into (9) yields

$$e(t) = [4E/\pi D]\ \alpha \int_{-\ell}^{\ell} r \frac{\partial\rho}{\partial x}\, dy. \tag{12}$$

Now let

$$s = \frac{4E}{\pi D} \cdot r, \tag{13}$$

where s is generally referred to as the "sensitivity" of the system. Then equation (12) becomes

$$e(t) = \alpha \int_{-\ell}^{\ell} s \frac{\partial\rho(y,t)}{\partial x}\, dy. \tag{14}$$

The time dependence of the signal is a result of time-varying disturbances passing through the beam.

The easiest operation to perform on e(t) is to compute its root-mean-square (RMS) value:

$$e_{RMS} = \sqrt{\overline{e^2}}\ . \tag{15}$$

This can be accomplished simply with an RMS meter (e.g., a Ballantine True RMS Meter Model 320A). It would be a simple matter to attach a small panel to the RMS meter having one red light and one green light to indicate when the RMS value of the signal (intensity of the disturbances) is above or below some established critical value.

Our goal is to have a continuous gross "picture" of the intensity of disturbances over the entire runway. A single laser beam as described above would not meet this requirement; however, several beams (a laser net) could.

In figure 5 a "laser net" is shown for monitoring wingtip vortices. Each beam in the net is essentially the same as the single beam discussed previously. Although the "laser net" appears to be a much more complicated system than the single beam, this is not actually the case. By connecting the outputs of all detectors in the net, the entire area covered by the net can be monitored from one signal, e_T:

$$e_T = e_1 + e_2 + e_3 + \ldots + e_m \tag{16}$$

$$e_T = \sum_{k=1}^{m} e_k \tag{16a}$$

and

$$\overline{e_T^2} = \sum_{k=1}^{m} \overline{e_k^2} + \sum_{k=1}^{m} \sum_{\ell=1}^{m} \overline{e_k e_\ell}, \qquad k \neq \ell. \tag{17}$$

Because the density gradient fluctuations are expected to be produced by small scale random temperature inhomogeneities which are uncorrelated over long distances, the quantity

$$\overline{e_k e_\ell}$$

should be zero. Thus, equation (17) becomes:

$$\overline{e_T^2} \doteq \sum_{k=1}^{m} \overline{e_k^2}, \tag{18}$$

where m is the number of beams in the net. Taking the square root of both sides of equation (20) gives

$$e_{T_{RMS}} = \sqrt{\sum_{k=1}^{m} \overline{e_k^2}} \quad . \tag{19}$$

Equation (19) shows that it is just as easy to monitor a net of laser schlieren beams as it is to monitor one. A schematic of the laser net system described above is shown in figure 6.

Although the laser schlieren system is sensitive to wingtip vortices, it is also sensitive to density gradient fluctuations produced by heating and other atmospheric disturbances. Thus, the magnitude of the average RMS value of the schlieren signal on a cool calm day would be considerably less than it would be on a hot windy day. However, on either day a wingtip vortex intersecting the beams would produce a sudden rise in the RMS value of the signal.

A sudden change in the magnitude of the RMS value of the signal, $\Delta e_{T_{RMS}}$, could be detected by monitoring the difference between a RMS value of the signal computed over a "long" time, T_1, and another computed over a "short" time, T_2 (i.e., $T_1 \gg T_2$).

$$\Delta e_{T_{RMS}} = e'_{T_{RMS}} - \overline{e_{T_{RMS}}} \; , \tag{20}$$

where $\overline{e_{T_{RMS}}}$ is computed during time T_1 and $e'_{T_{RMS}}$ is computed during time T_2.

In practice, this could be accomplished by monitoring the difference between the outputs from two RMS meters, one having an integration time, T_1, and one having an integration time, T_2. Figure 7 is a schematic of a system which could be used to monitor $\Delta e_{T_{RMS}}$.

III. THE EXPERIMENT

An experiment was performed to determine (1) if a trailing wingtip vortex would produce a fluctuating signal sufficiently larger than the combined instrument noise and turbulent flow "noise" to make the presence of the vortex readily detectable and (2) if the fluctuating signal would increase with increasing vortex strength. The experiment was a cursory attempt to determine the feasibility of measuring the strength of wingtip vortices with a laser schlieren system.

The experiment was performed in a low-speed wind tunnel with an 8.4 cm by 8.9 cm transparent plastic test section (see figure 8). The wingtip, which had a tip chord of 3.3 cm, was mounted on the floor of the test section. The vortex was made "visible" in figure 9 by a tuft of thread attached to the wingtip.

The instrumentation consisted of (1) a low-noise helium-neon laser (Perkin-Elmer model 5200, $\lambda = 6328\mathring{A}$), (2) a photodetector placed approximately one meter from the tunnel centerline and consisting of a knife-edge and an EG&G model S-D100 photodiode, (3) a Redcor model 500 amplifier, and (4) a Ballantine model 320A True RMS Meter. The flow speed for all measurements was approximately 15 meters per second.

Figure 10 shows the oscilloscope records for three different conditions: (a) no flow instrument noise, (b) the wind on but the airfoil not installed, and (c) wind on with airfoil installed at 15 degrees angle of attack and the laser beam positioned 5 cm behind the trailing edge and at the same height (2.5 cm) as the tip. The increase in signal level from figure 10(a) to 10(b) is probably due primarily to the wind tunnel wall boundary layer. The increase from figure 10(b) to figure 10(c) clearly indicates that the presence of the vortex is easily detectable. High- and low-pass filters were used to provide an electronic band-pass from 200 to 10,000 cps. This band-pass was used for all runs. The relatively high frequency signal in figure 10(c) is thought to be due to small-scale density inhomogeneities within the vortex which were carried through the laser beam by the motion of the vortex.

Figure 11 gives the results of a traverse of the laser beam, at wingtip height, downstream from the airfoil. The variations in RMS signal were not large; they are probably within the accuracy to which the RMS meter could be read, because the fluctuations in needle position were rather large.

Figure 12 shows the variation in RMS signal level with airfoil angle of attack. The laser beam was 5 cm downstream of the trailing edge and at wingtip height. The RMS value of the signal increases dramatically with increasing angle of attack, or vortex strength. Perhaps one reason for this large increase in signal is that more and more turbulence from flow separation gets mixed into the vortex with increasing angle of attack. Although the RMS value might not be related to the vortex strength alone, this figure gives hope for the success of the method.

IV. CONCLUDING REMARKS

This preliminary study indicates that the proposed laser net wingtip vortex monitoring system might be a workable idea because the presence of a vortex is definitely detectable, and increasing the strength of the vortex increases the RMS signal. If, indeed, a relation between vortex strength and RMS signal can be established through further investigation, the laser net system would become a promising method for monitoring wingtip vortices on runways.

The primary disadvantages of this system are that (1) towers, or supporting poles, are required along the runway to hold the lasers and detectors and (2) the approach lanes above tower heights cannot be monitored. However, the first objection can be overcome by using telescoping poles which can be retracted underground during takeoffs and landings. The important period for making measurements is before a takeoff or landing; no measurement need be made after an airplane is committed to the takeoff or landing. Also, the second objection might not be so serious as it seems at first. An airplane normally generates its maximum lift near the ground on landing and takeoffs; therefore, the wingtip vortices will be strongest near the ground within the laser net field. So, when the laser net indicates that the strong vortices near the runway have decayed to an acceptable level, one could reasonably expect that the weaker vortices at higher altitudes have also decayed to an acceptable level. Or, if the wind on the ground blows the vortices off the runway and out of the laser net, one could reasonably expect that the greater winds at higher altitudes had already blown the vortices out of the flight path. In addition, it seems that the space just above the runway is the most important space to monitor because a serious disturbance to an aircraft near the ground would be more likely to lead to disaster than the same disturbance at higher altitude.

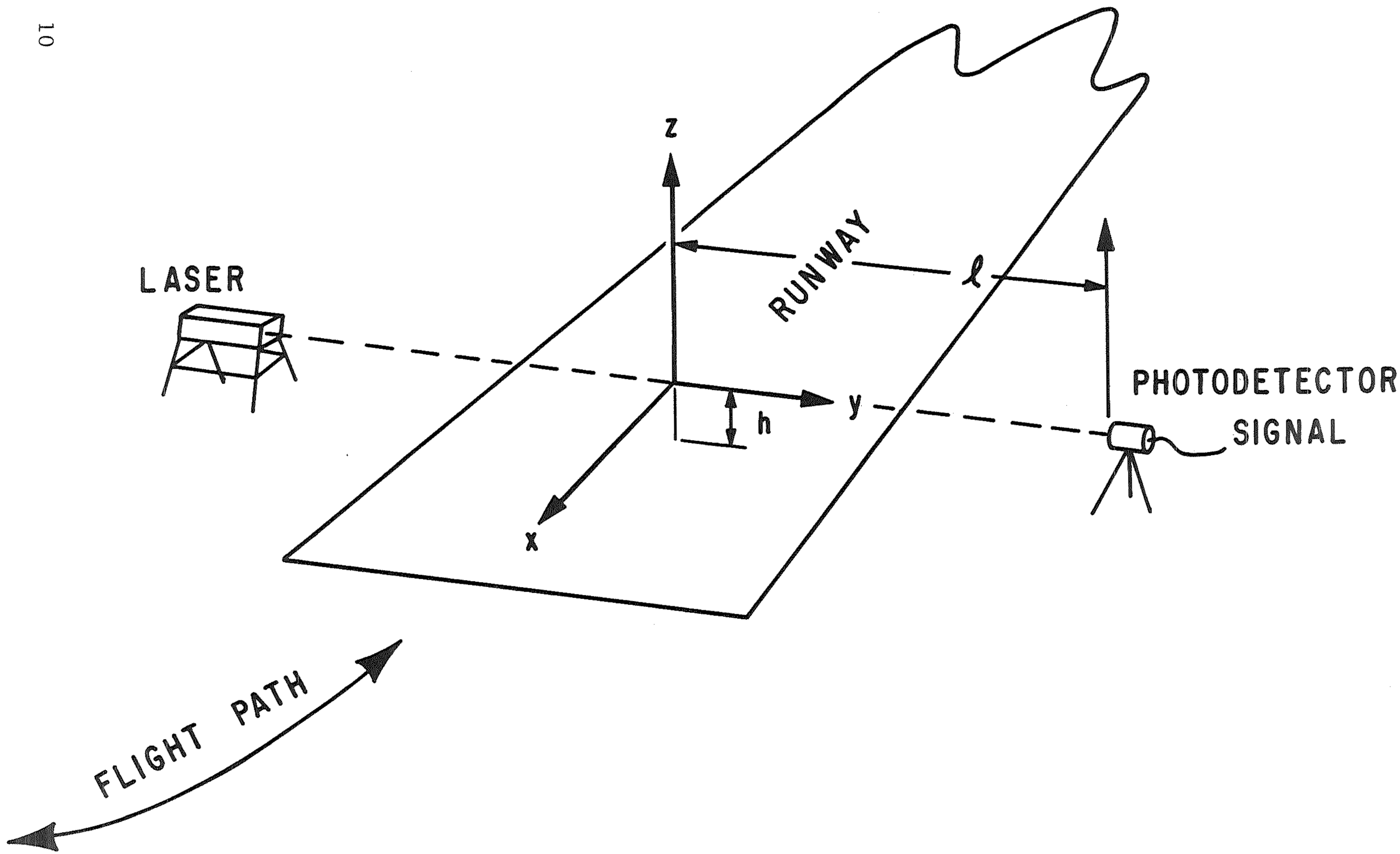

Figure 1. Single Beam Laser Schlieren System

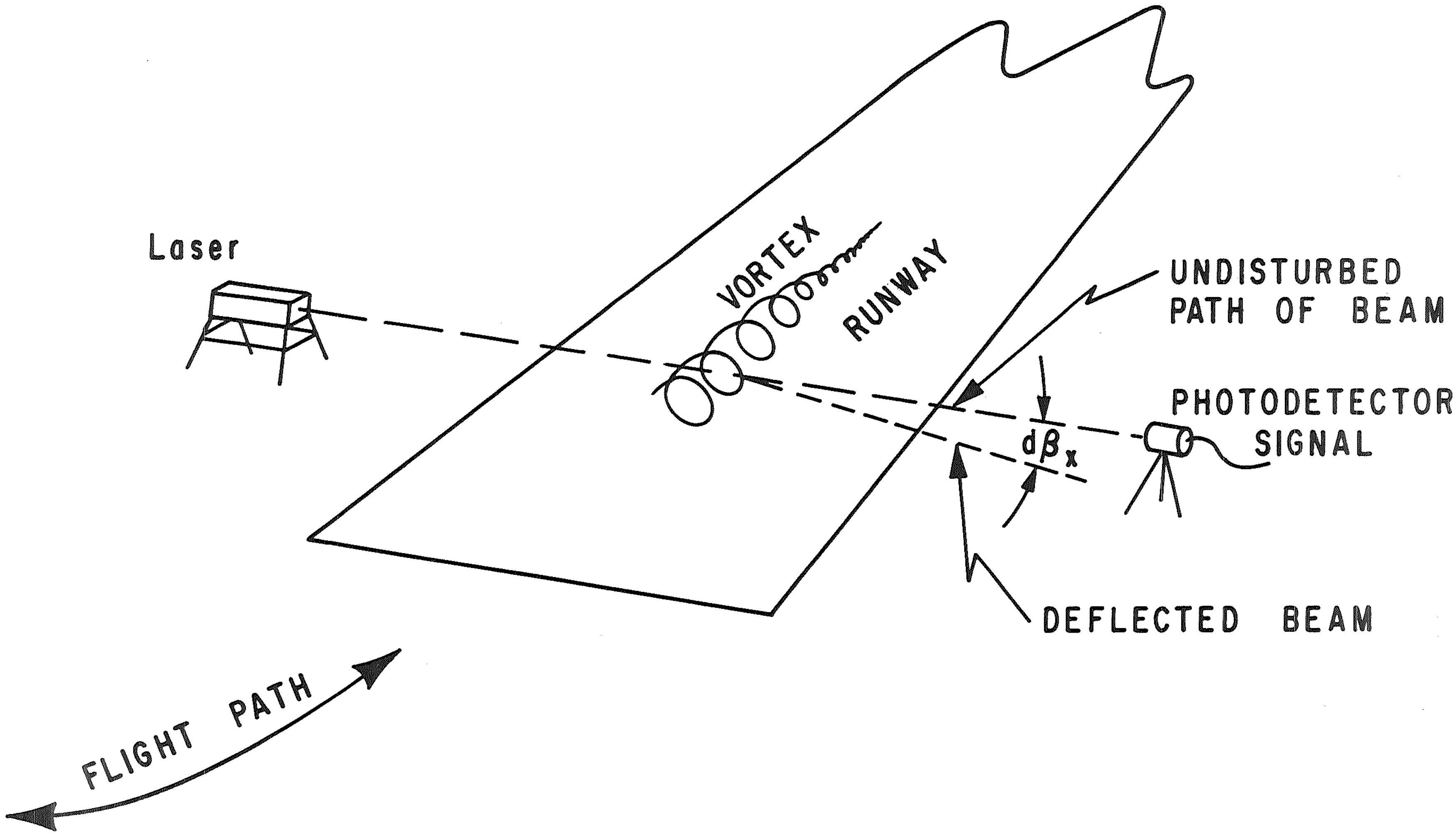

Figure 2. Schematic Showing Laser Beam Deflected by Vortex

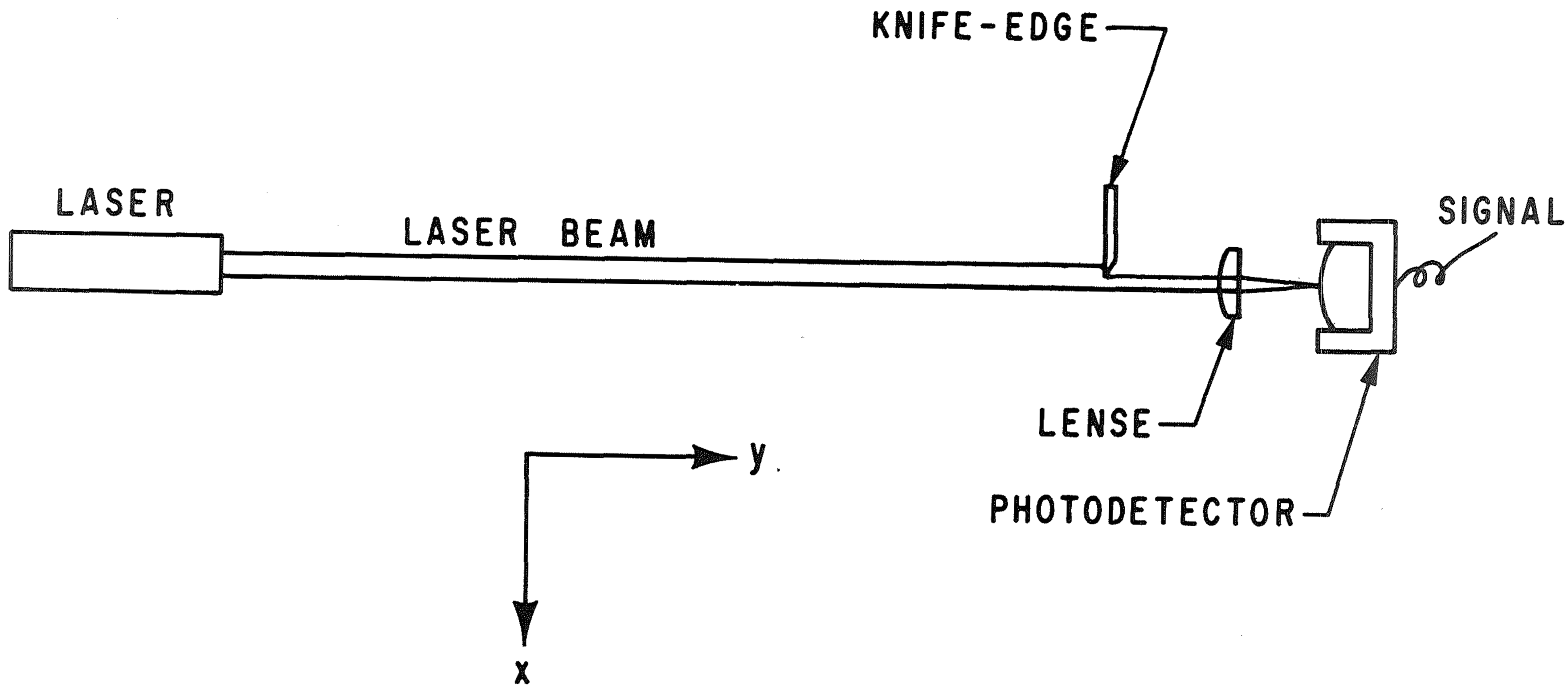

Figure 3. Schematic of a Laser Schlieren Beam with Detector

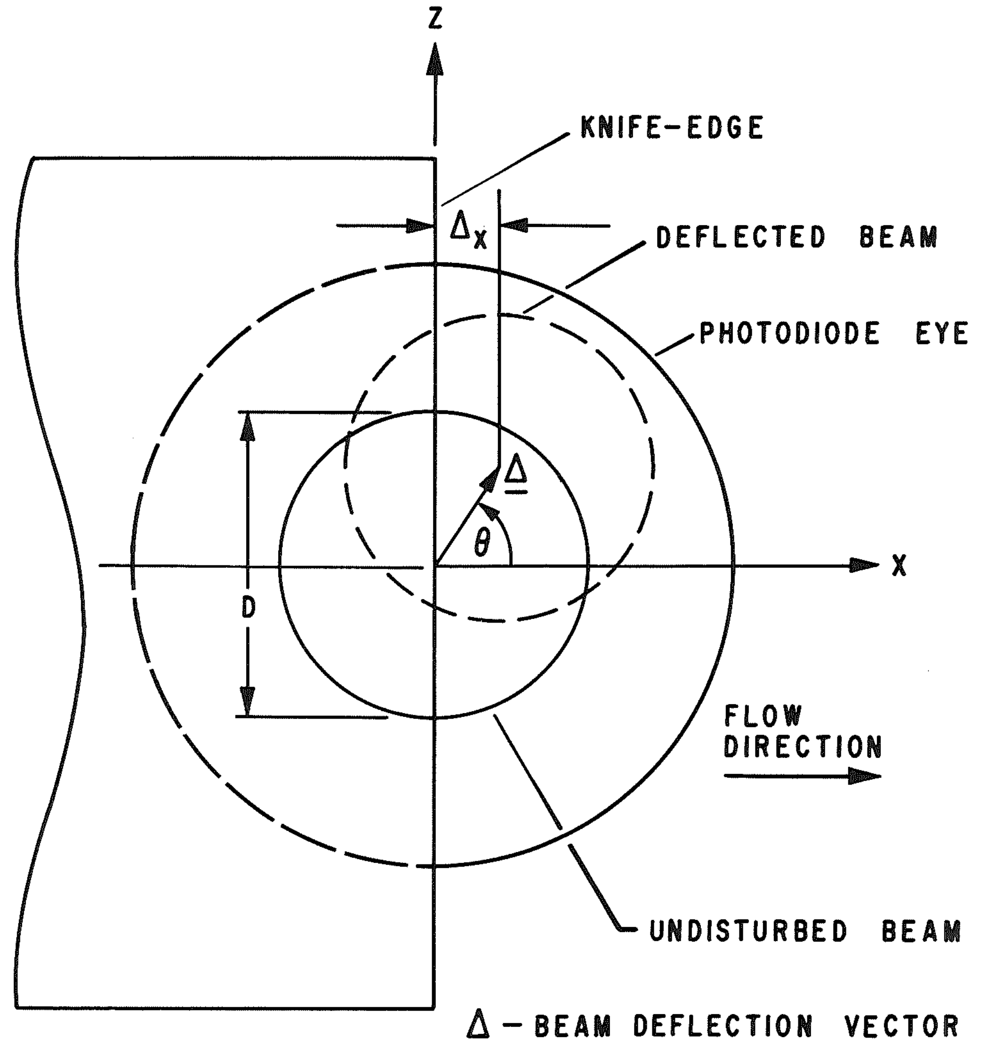

Figure 4. A Schematic of a Cross Section Taken Across One Beam of a Laser Schlieren System

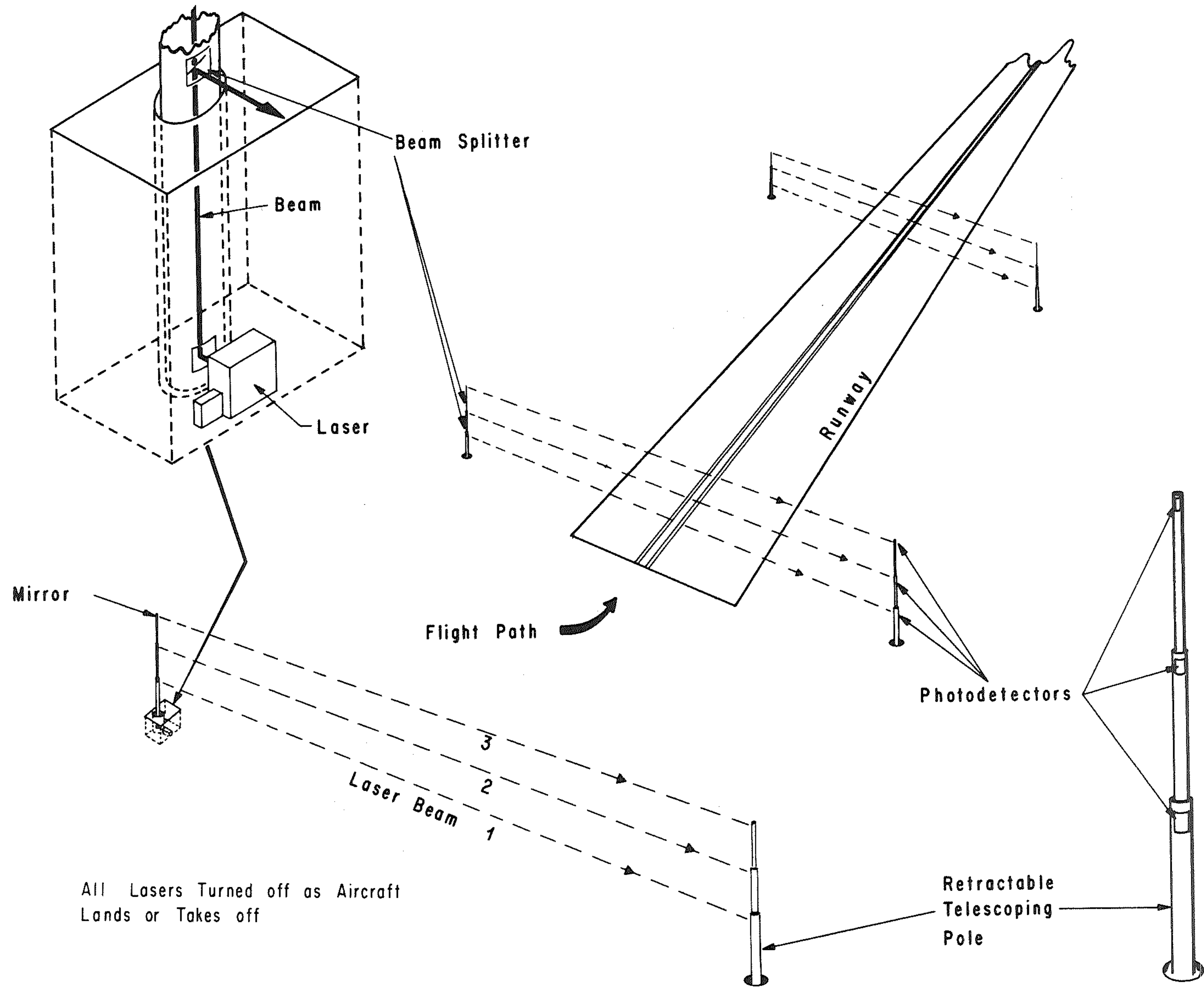

Figure 5. Schematic of a "Laser Net" Laser-Schlieren
Monitoring System for Airport Runways

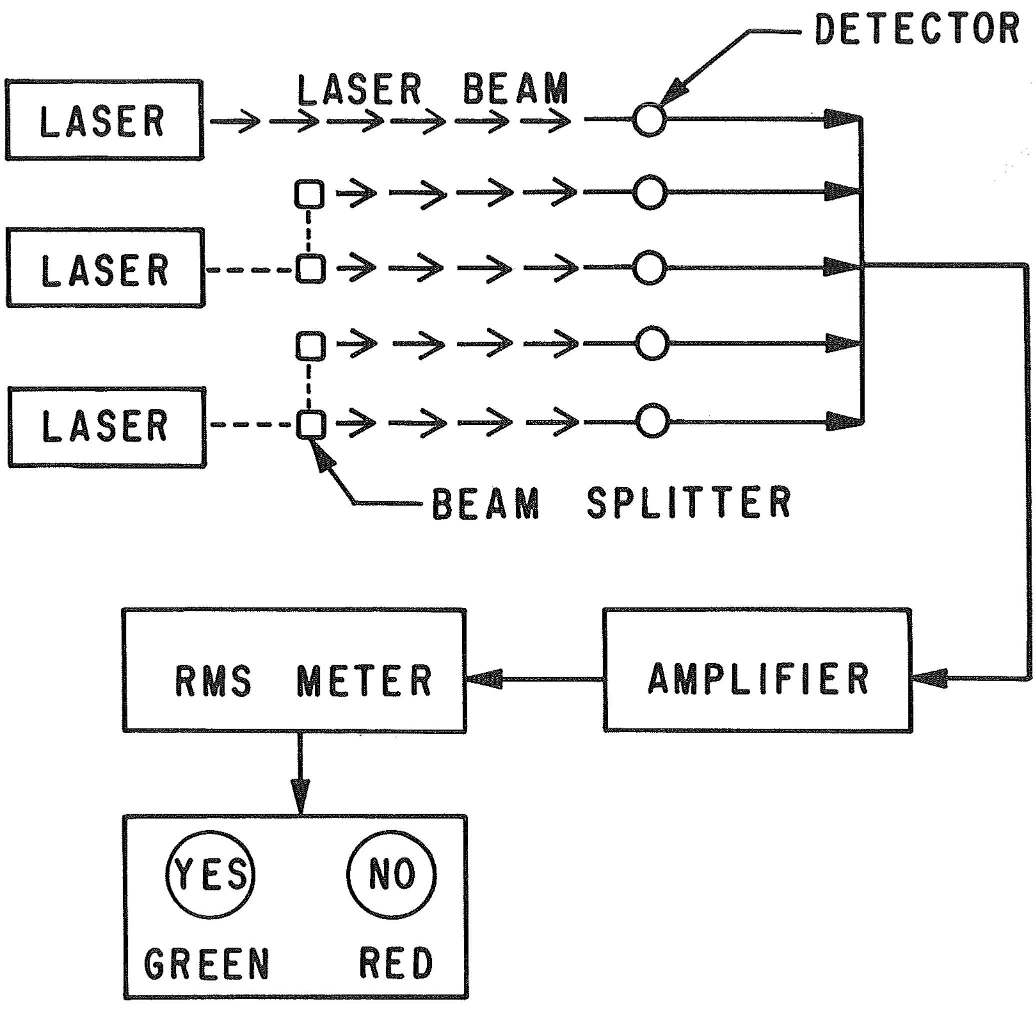

Figure 6. Schematic of Laser Net Instrumentation

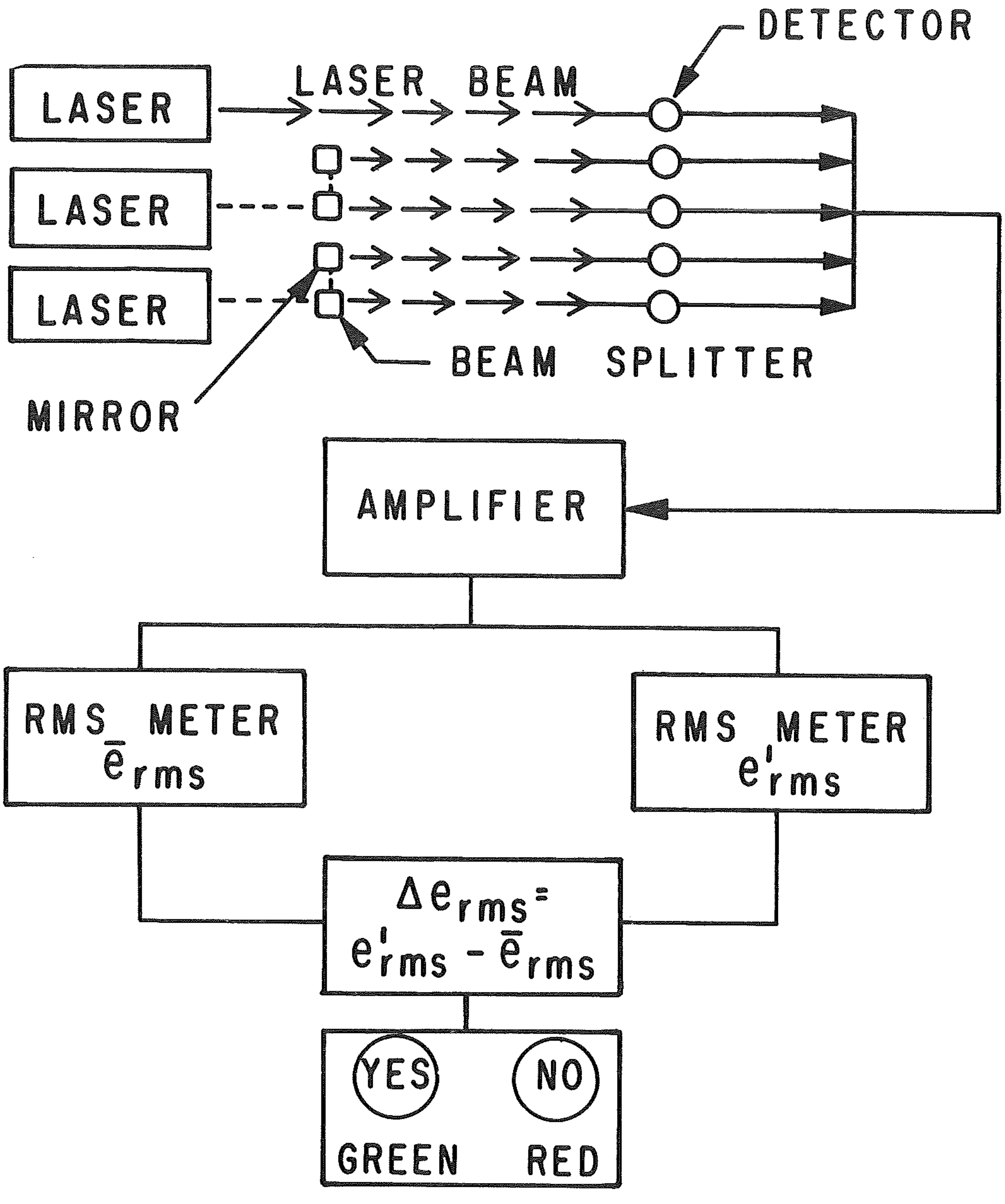

Figure 7. Schematic of Instrumentation for Monitoring Sudden Changes in RMS Value of Signal

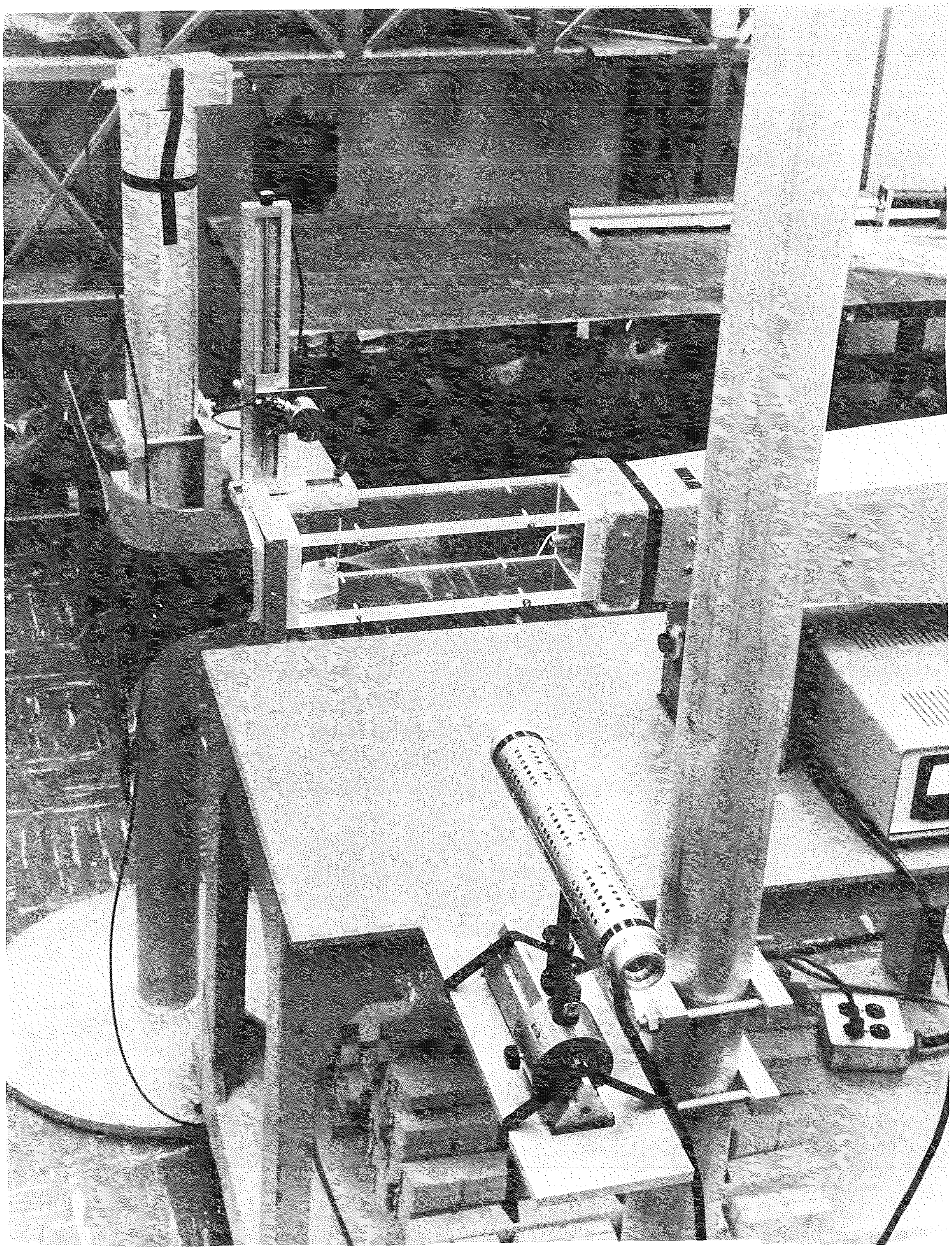

Figure 8. Wind Tunnel and Apparatus

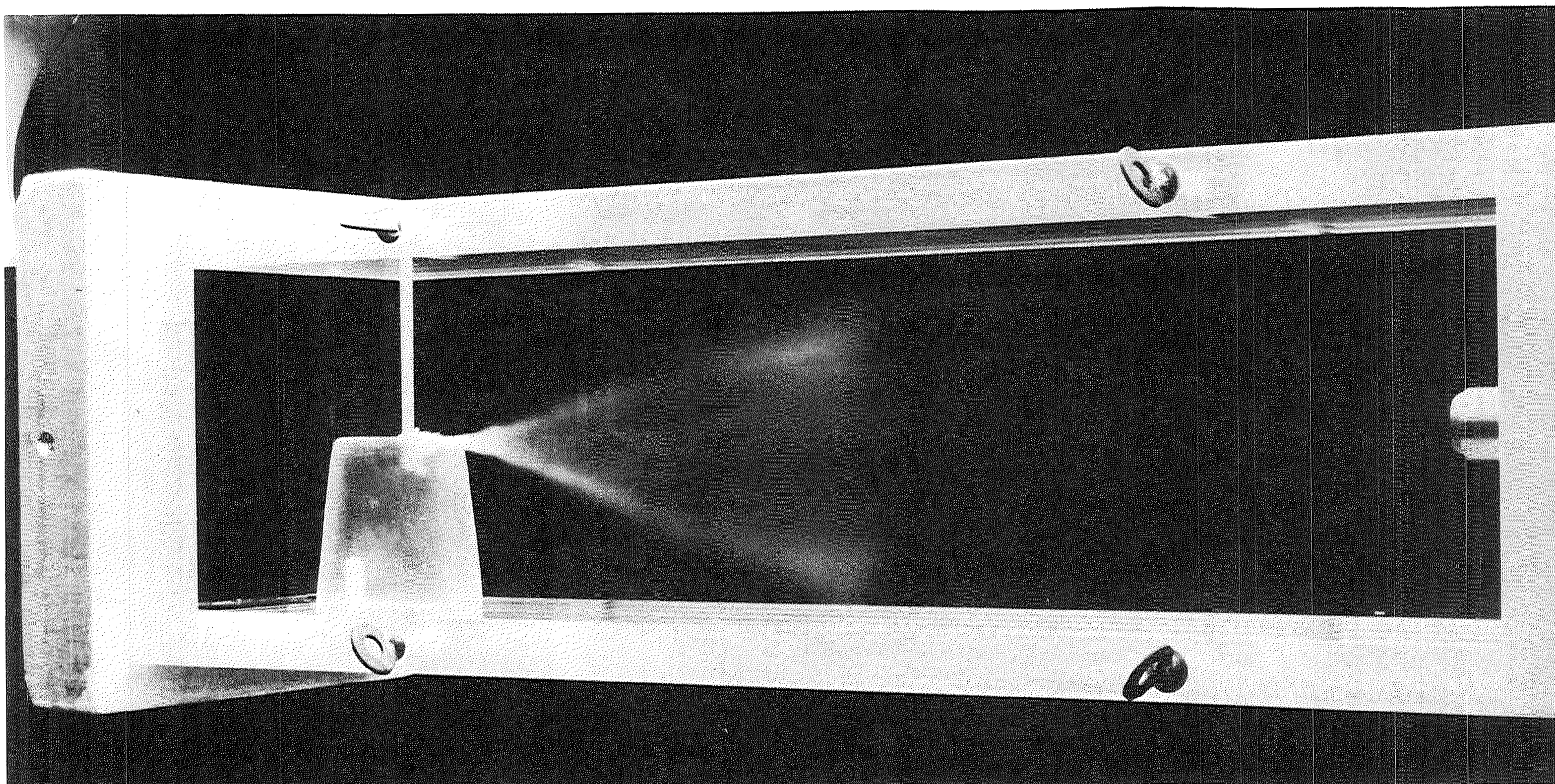

Figure 9. Airfoil Showing the Tuft Pattern

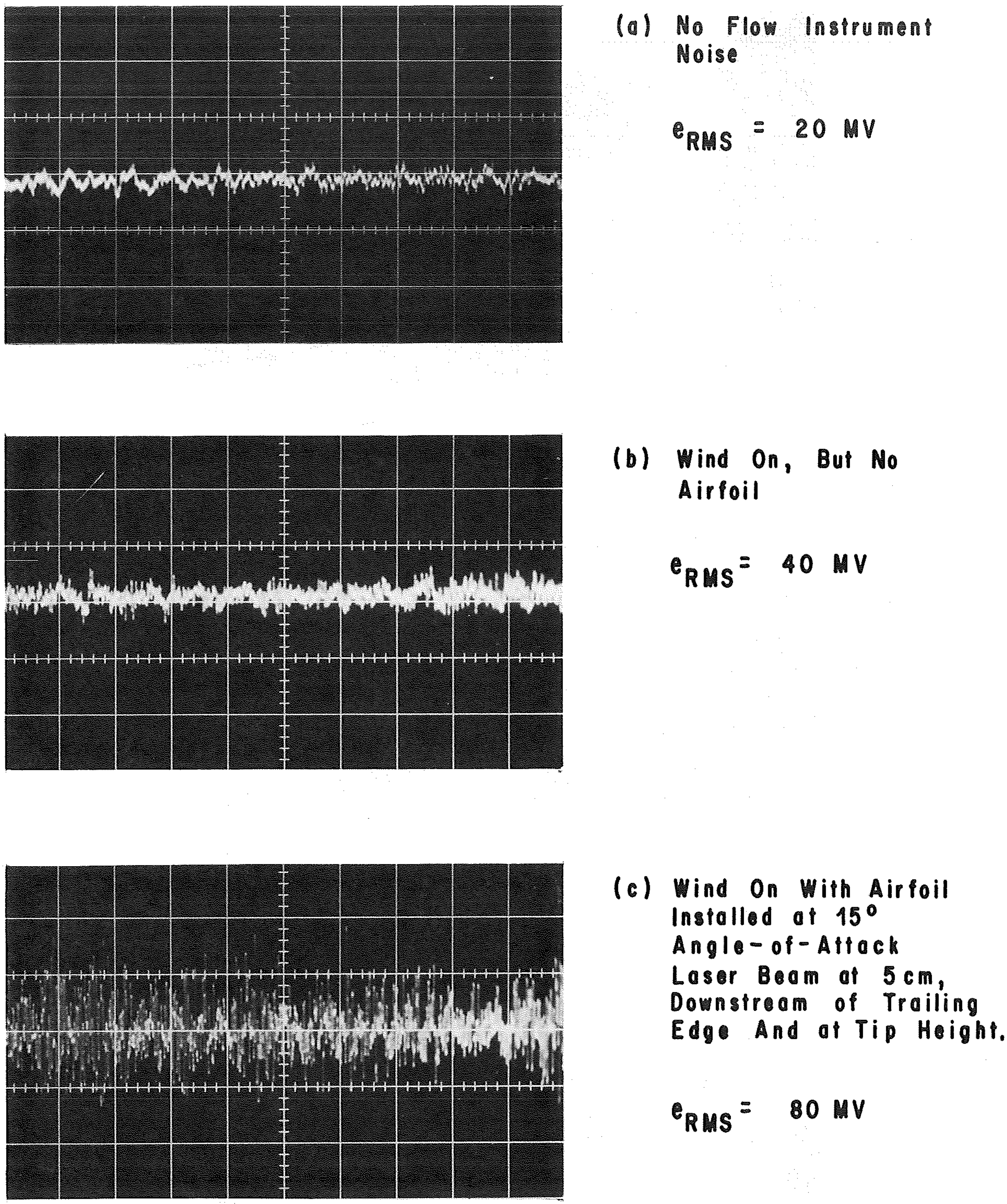

Figure 10. Signal Display (Gain = 100,000, Sensitivity = 0.2 volts/cm, Sweep Rate = 5 ms/cm)

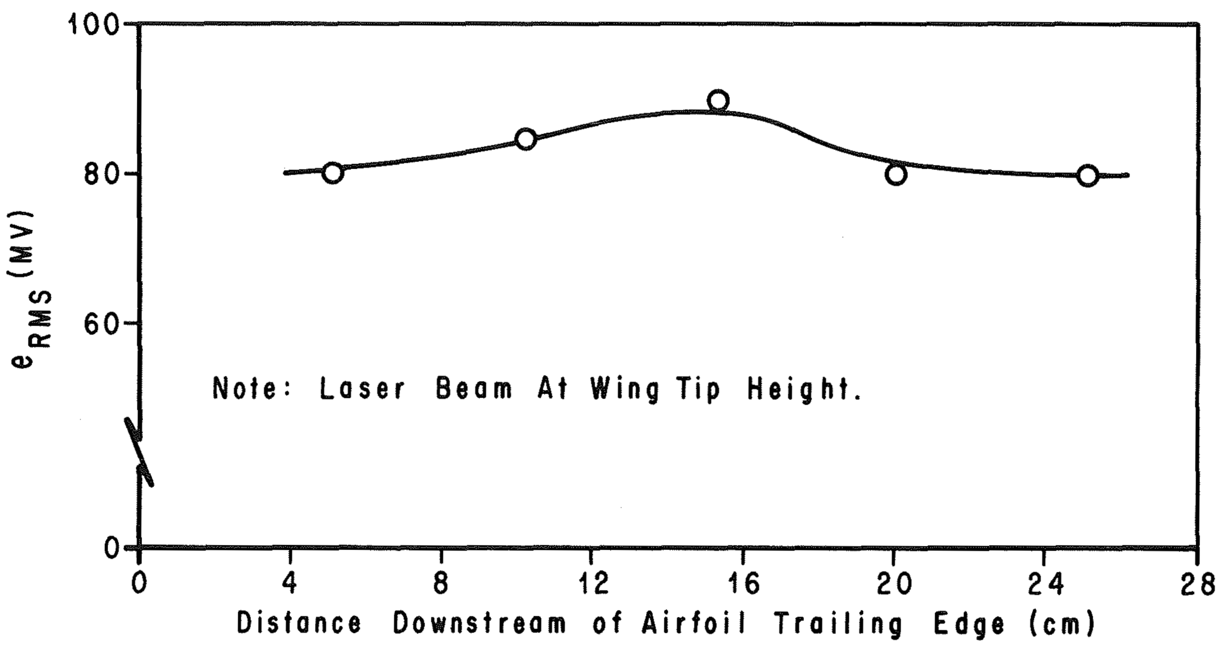

Figure 11. Intensity of Disturbances vs Distance from Airfoil

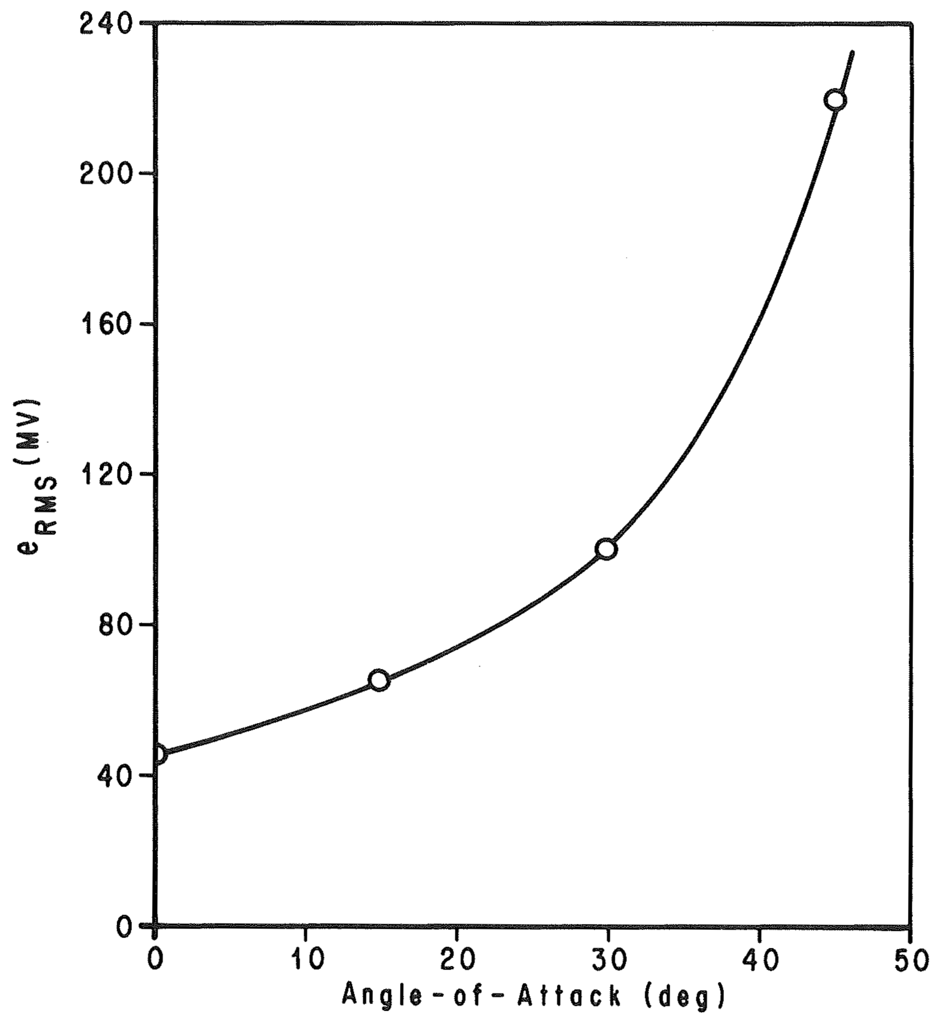

Figure 12. Intensity of Disturbances vs Angle of Attack

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